ARTICLES
https://doi.org/10.1038/s43016-022-00549-0

nature food

Time management governs climate resilience and productivity in the coupled rice–wheat cropping systems of eastern India

Andrew J. McDonald[1], Balwinder-Singh[2] ✉, Alwin Keil[3], Amit Srivastava[4], Peter Craufurd[5], Avinash Kishore[6], Virender Kumar[7], Gokul Paudel[5], Sudhanshu Singh[4], A. K. Singh[8], R. K. Sohane[9] and R. K. Malik[10]

India will need to produce 30% more wheat by 2050, and these gains must principally come from intensification in eastern India where low productivity is common. Through a dense network of on-farm surveys for the rice–wheat system in this region, we show that contemporary wheat sowing dates have a central influence on achieved and attainable yields, superseding all other crop management, soil and varietal factors. We estimate that untapped wheat production potential will increase by 69% with achievable adjustments to wheat sowing dates without incurring undesirable trade-offs with rice productivity, irrigation requirements or profitability. Our findings also indicate that transformative gains in wheat yields are only possible in eastern India if rice and wheat are managed as a coupled system. Steps taken to 'keep time' through better management of the annual cropping calendar will pay dividends for food security, profitability and climate resilience now and as a foundation for adaptation to progressive climate change.

Wheat is a principal crop staple in South Asia with current cultivation extending across 36.1 million ha; around 73% of this area is in India where wheat provides approximately 21% of the aggregate food energy and 17% of the dietary protein on a national scale[1]. Projections suggest that wheat production in India alone will need to increase from current levels of around 110 million tons to 140 million tons by 2050 to keep pace with domestic requirements[2,3]. Because reserves of potentially cultivatable land are extremely low in South Asia[4], future production increases must emerge from yield intensification rather than cultivated area expansion. Hence, identifying the magnitude and causes of wheat yield gaps (that is, the difference between potential and achieved crop productivity) is essential for prioritizing and effectively targeting policies and programmes for sustainable agricultural development.

South Asia's principal wheat growing area is the Indo–Gangetic Plain, where dry-season wheat is commonly grown in rotation with wet-season rice (that is, the rice–wheat system; hereafter referred to as the RW system). The RW system occupies about 10 million ha in India[5]. The Western Indo–Gangetic Plain includes the Indian states of Punjab and Haryana and has the highest mean levels of wheat productivity in the region (4.5 t ha^{-1}). However, modest yield gaps (9–12%) (ref. [6]) together with accelerating production challenges such as groundwater depletion have drawn into question the long-term sustainability and potential for yield intensification in these states[7–10]. As a consequence, Indian policymakers have prioritized staple crop intensification in the Eastern Ganges Plain (EGP) region, including Bihar state and the eastern districts of Uttar Pradesh state through initiatives such as Bringing the Green Revolution to eastern India to meet current and future food security challenges.

Wheat yield gaps in the EGP are among the highest in India[6,11] and have been variously attributed to a range of factors, including late sowing, use of older cultivars, complex weed flora, variable access and low utilization of irrigation water and labour shortages[8,12–14]. Late wheat sowing creates substantial climate hazards from heat stress by delaying crop reproductive growth into the spring period (that is, March through early April) when temperatures warm considerably. Heat stress reduces photosynthetic efficiency and can shorten the grain-filling duration through premature crop senescence, thereby reducing biomass production, harvest index and crop yield[15,16]. Although several studies have confirmed the importance of timely sowing for avoiding yield losses from heat stress[17–19], the contribution of current sowing date patterns to yield gaps is insufficiently characterized in South Asia. Moreover, few contemporary studies assess the enabling factors that determine the capacity of farmers to make sowing date adjustments[20]. It is also important to note that the RW systems of South Asia are not simply a set of crops grown in sequence but rather reflect an interlinked set of management decisions that often involve yield or sustainability trade-offs[5,10]. Consideration of yield gaps is no exception and must be conceptualized at the cropping system level rather than for wheat alone[21]. In the context of this study, we use the concept of 'climate resilience' to refer to the capacity of planting date adjustments to

---

[1]Soil and Crops Sciences—School of Integrative Plant Science, Cornell University, Ithaca, NY, USA. [2]Department of Primary Industries and Regional Development, Northam, Western Australia, Australia. [3]unique land use GmbH, Freiburg, Germany. [4]International Rice Research Institute (IRRI)—South Asia Regional Centre (ISARC), Varanasi, India. [5]International Maize and Wheat Improvement Center (CIMMYT), South Asia Regional Office, Lalitpur District, Nepal. [6]International Food Policy Research Institute (IFPRI), National Agricultural Science Complex (NASC), New Delhi, India. [7]International Rice Research Institute (IRRI), Los Baños, Philippines. [8]Indian Council of Agricultural Research (ICAR), New Delhi, India. [9]Bihar Agricultural University (BAU), Sabour, India. [10]International Maize and Wheat Improvement Center (CIMMYT), National Agricultural Science Complex (NASC), New Delhi, India.
✉e-mail: balwinder.singh@dpird.wa.gov.au

enhance crop yields, yield potential and yield stability by reducing exposure to less favourable growing conditions[22].

By combining field and household survey data, time series remotely sensed information and dynamic crop simulation, this study of RW systems in the EGP of India has four interlinked objectives: (1) quantification of the importance of planting dates to current wheat yields, yield potential (Y_p) and yield gaps (YG), (2) ex ante opportunity assessment of gains in wheat yield potential achievable through planting date adjustments, (3) identification of enabling and constraining factors that contribute to the timing of wheat planting and (4) simulation-based assessment of RW system-level strategies for enhancing climate resilience through planting date adjustments. Together, these objectives seek to establish the importance of cropping calendar management ('keeping time') to the performance of RW systems in the stress-prone EGP to inform sustainable intensification and climate adaptation strategies in the region.

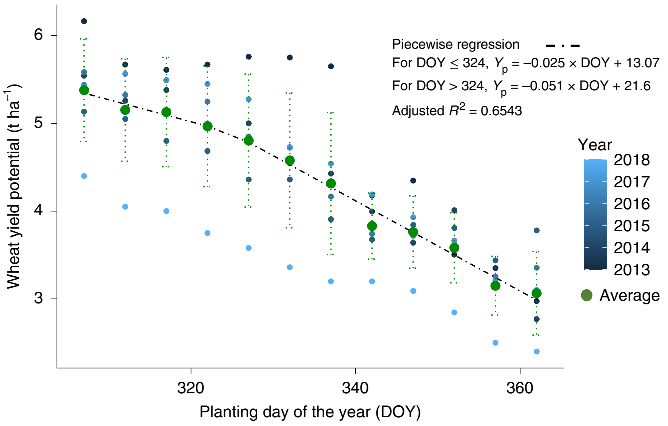

Fig. 1 | Sowing date and wheat yield potential. At 5 d intervals, field survey data ($n = 11,413$ production fields) and boundary line analysis were used to estimate wheat yield potential (Y_p) as a function of establishment date for six consecutive production seasons (2013–2018 harvest years). Mean values across years are depicted in green with associated error bars representing ±1 standard deviation (SD) from the mean. The black line is the 'best-fit' piecewise regression with a break point at 20 November (DOY 324) after which declines in yield potential with sowing date delays doubles from 25 kg ha^{-1} d^{-1} to 51 kg ha^{-1} d^{-1}.

Results

Sowing date and climate-resilient wheat production. To contextualize the overall significance of wheat establishment dates to actual yield outcomes under the diversity of cropping system factors in the study's area of interest (AOI), machine learning analytics were applied to on-farm observational data from landscape-scale diagnostic surveys. The absolute and relative importance of factors that are influenced by management decisions were determined. Two different models were developed to reflect the enhanced nature of the survey questionnaire, soils data and sampling design in 2018. Farmer-estimated wheat yields were reported in 2018, whereas physical crop cuts were conducted in previous years, an approach that is probably more reliable but also more difficult and costly to implement at scale. Despite characterizing a richer set of system characteristics in 2018, this difference in yield assessment methods probably explains the slightly inferior validation R^2 (0.40) and modest improvement in RMSE (0.67 t ha^{-1}) values compared with the model developed for 2013–2017. That said, both models identified sowing date as the strongest predictor of yield outcomes (Supplementary Table 1).

From the 2018 survey year, the median sowing date was 27 November with an interquartile range from 20 November to 5 December. Across the entire survey sample, the mean wheat yield (Y_{actual}) was 2.9 t ha^{-1}. By segregating the data into planting date terciles, that is, early (before 20 November), medium (20 November to 4 December) and late (after 4 December), a clear pattern emerges with mean early sowing yields (3.4 t ha^{-1}) greatly exceeding both average (2.9 t ha^{-1}) and later sowing dates (2.5 t ha^{-1}). Farmers sowing early achieved wheat productivity levels nearly 1 t ha^{-1} higher than those sowing late, representing a 36% increase in achieved yields.

Boundary line analysis and linear regression was used to estimate the influence of planting date on wheat yield potential (Y_p) by combining survey data from six cropping seasons (Fig. 1). The best-fit regression model was a two-segment 'piecewise' model with a break point at day of year (DOY) 324, or 20 November. Before this date, every day delay in wheat planting resulted in a Y_p loss of approximately 25 kg ha^{-1} d^{-1}. After this point, losses approximately doubled to 51 kg ha^{-1} d^{-1}. These results suggest that Y_p increases by 69% for fields established in early November ($Y_p = 5.4$ t ha^{-1}) compared with those sown in late December ($Y_p = 3.2$ t ha^{-1}). Year-to-year stability of Y_p also changes after 20 November with the standard deviation increasing by approximately 30% over earlier sowing dates, implying that system reliability diminishes considerably with later establishment. Stability is regained with very late sowing in mid-December with consistently low values across years.

Satellite estimates of wheat sowing dates. On an area-wide basis, the MODIS-derived wheat sowing date estimates for harvest years 2003 to 2017 suggest a multi-year mean of 13 December that ranges for individual years from 5 December to 19 December with a SD ± 4 d (Fig. 2). There are, however, notable geographic differences with interannual sowing date stability associated with areas that are usually planted in either early November or late December (that is, well-drained or poorly drained parts of the landscape, respectively). At the pixel level, there is also considerable spatial variability within years (SD ± 11 d) with the southwestern part of the study area considerably delayed whereas the northwest and central region are generally early. Nevertheless, in an average year, our analysis suggests that a dominant share of the wheat area (59%) in the study's AOI is sown after 1 December.

Drivers of wheat sowing dates. In the household survey conducted in a subset of six districts for the wheat harvest years of 2010 to 2015, farmers were asked about their normal wheat planting practices and, as appropriate, causes of delayed wheat sowing (that is after 15 November for the purposes of the survey). Out of 5,766 responses, wheat was sown late in 4,857 cases (84%) (Table 1). Overall, the three most prominent reasons for late sowing were that the field was still occupied by the previous crop (44%), almost always rice, followed by knowledge gaps about the importance of early sowing (26%) and field waterlogging from poor drainage (21%). Disaggregating the results by survey periods shows that the share of late-sowing farmers who were not aware of the benefits of earlier sowing decreased substantially from 37% (2010–2012) to 14% (2013–2015). Conversely, cases where the field was still occupied by rice more than doubled from 28% to 61%, probably in part because of a two-week delay in the onset of monsoon rainfall in 2012.

Landscape diagnostic surveys conducted across the broader AOI of our study for the wheat harvest year 2018 confirm the primary importance of rice management to the timing of wheat planting. Before DOY 305 (that is, 1 November, approximately 25% of the dataset), there is no apparent association between rice harvest and wheat sowing date. After 1 November, a strong linear relationship exists with each day of delay in rice harvest accounting for a 0.8 d delay in wheat establishment (Fig. 3). Across all rice harvest dates in 2018, the median time lag between rice harvest and wheat establishment was 15 d with the highest quartile delayed by ≥23 d.

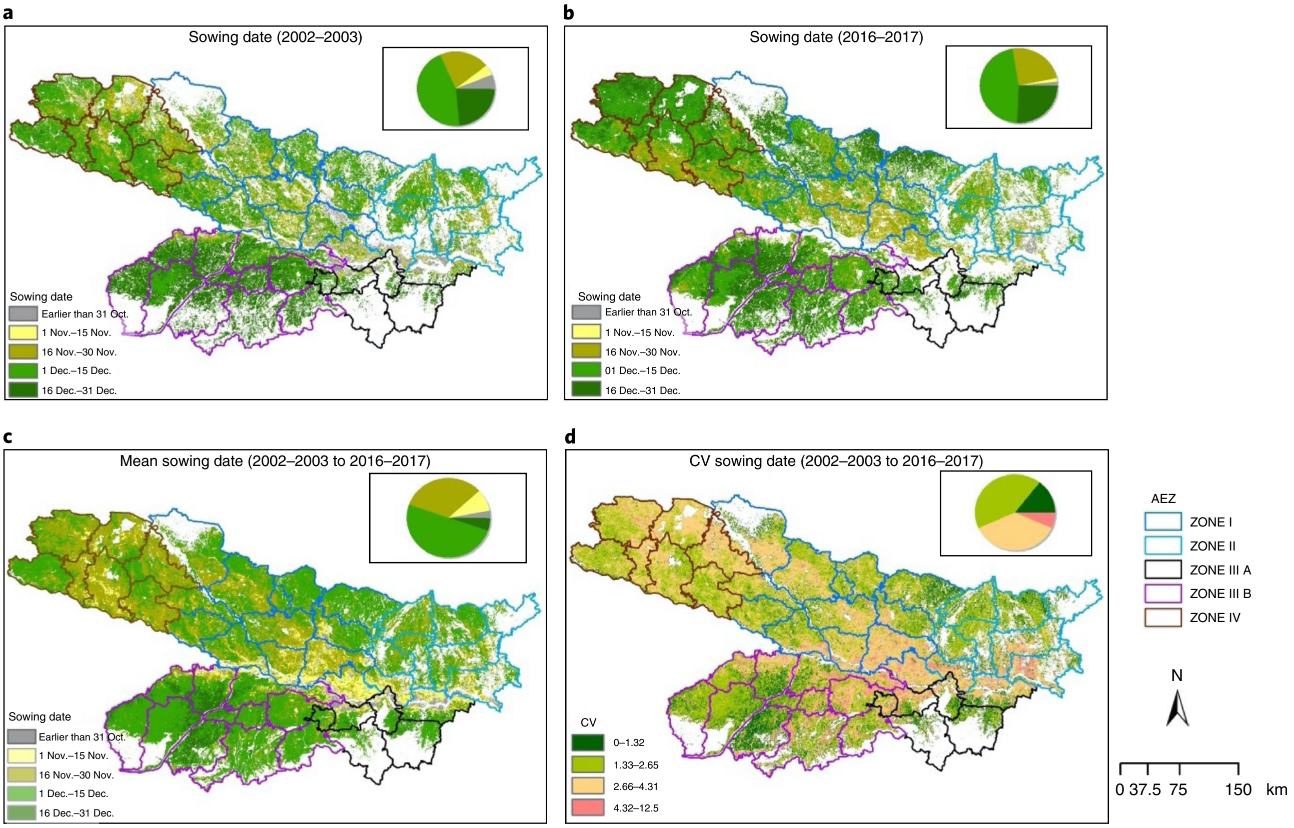

Fig. 2 | Satellite-based assessment of regional wheat sowing date patterns. Long-term (2003–2017 wheat harvest seasons) analysis of MODIS satellite imagery characterizes spatial and temporal patterns of wheat sowing dates at the scale of 250 m in eastern India. Spatial distributions of wheat sowing dates in the most delayed sowing year (**a**) and in the earliest (**b**). The multi-year average sowing date (**c**) and the degree of sowing variation across years as characterized by the coefficient of variation (CV) (**d**). Pie chart shows the percentage of total wheat area under different sowing date categories (**a**–**c**) and under categories of CV. AEZ, Agroecological Zone.

Table 1 | Farmer-stated reasons for delayed wheat sowing

	(1) 2010-2015	(2) 2010-2012	(3) 2013-2015
	(*n* = 4,857)	(*n* = 2,488)	(*n* = 2,371)
I see no reason to sow earlier	25.8	37.1	13.9
Field still occupied by previous crop	44.0	27.7	61.2
Field waterlogged	20.8	29.2	12.0
Followed extension advice	1.5	0.8	2.1
Lack of capital	2.2	0.8	3.7
Lack of labour	1.4	1.6	1.2
Delayed availability of wheat seed	0.4	0.1	0.7

Recall surveys in six districts of Bihar, India, identified causes of late wheat sowing (>15 November) expressed as percentages of total farmer respondents (*n* = 5,766 site years). Column 1 summarizes across all years with column 2 reporting the first three and column 3 the past three sowing years captured in the survey. Knowledge of the importance of early sowing appeared to have increased with time, a dynamic attributable to intensive extension efforts in the study area. Conflicts with delayed rice harvest caused late wheat sowing for 44% of the sample and constituted the dominant delay factor (66%) in the past three years of the survey.

Most farmers in this part of India wait until the onset of pre-monsoon showers to establish rice nurseries and for heavier monsoon rains to transplant the crop into the main field[23,24]. As estimated by satellite data, long-term averaged harvest dates suggests that 22% of the rice area is ready for harvest in the second fortnight of December, 47% in the first fortnight of December, 24% in the second fortnight of November and the remainder in the first fortnight of November. Spatial patterns of early and late rice harvest are associated with broad differences in drainage, with low-lying parts of the landscapes harvested last and, as a general rule, planted with longer-duration rice varieties.

Wheat yield gaps, productivity and profitability gains as influenced by sowing dates. For our AOI in Bihar and adjacent districts in eastern Uttar Pradesh, wheat Y_p is estimated to be 3.68 t ha^{-1} based on contemporary long-term mean planting dates (Scenario A). Wheat or rice-based interventions that serve the purpose of advancing wheat planting are expected to result in wheat Y_p gains of 0.30 (Scenario B) and 0.58 t ha^{-1} (Scenario C), respectively, whereas a combination of both interventions (Scenario D) is anticipated to increase wheat Y_p by 0.84 t ha^{-1} over current sowing date patterns. Accordingly, the yield gap for wheat would increase from 21% at present to 36% if both rice and wheat interventions were adopted. If wheat yield gaps are closed and Y_p is ultimately achieved, Scenario D would result in a gain of 1.88 million metric tons of annual production with an increase in farmgate value of US$421 m per annum over baseline planting conditions, that is, a 69% gain in untapped production potential and revenue over Scenario A. When implemented separately, rice planting date interventions are conservatively anticipated to have twice the impact of gains associated with wheat-focused planting date interventions (that is, shortening turn-around time between rice harvest and wheat planting) on

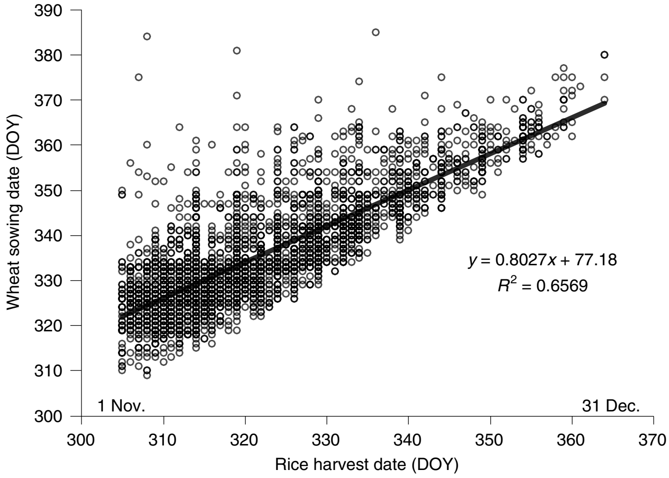

Fig. 3 | Wheat sowing date dependence on rice harvest date. Panel surveys from the same production fields in 2017 ($n = 5,538$, each field represented by a single symbol) demonstrates the strong dependence of wheat sowing date on the harvest date of the preceding rice crop. The median time lag between rice harvest and wheat sowing is 15 d. The black line is the linear regression for wheat sowing date as a function of rice harvest date; this relationship explains 65% of the total variation in wheat sowing date.

wheat Y_p. These results highlight the importance of managing RW rotations as a tightly coupled system rather than as separate crops (Table 2).

The opportunity to improve wheat yield potential through sowing date adjustments is not uniform across the study area. At the administrative block level, Y_p gains that exceed 1 t ha^{-1} over the current baseline (that is, Scenario A) are consistently observed in the northern half of the AOI, whereas responses in the southern blocks are mixed (Fig. 4). Gains are lowest in the southwest corner of Bihar state where poor field drainage at the end of the rice season limits opportunities for timely wheat sowing. In much of the central corridor of the AOI, earlier wheat planting is relatively more common. Hence, the wheat Y_p gains in this region are less than in the north where late sowing is pervasive.

Prospects for achieving climate-resilient RW systems. On the basis of current rice planting distributions in our study region[23], we anticipate that advancing the rice crop calendar by up to two weeks is technically feasible and generally advantageous from a wheat productivity perspective, except for those fields that remain too wet for wheat planting throughout November. The next fundamental question is whether an earlier rice establishment strategy for boosting wheat productivity has a positive, negative or neutral effect on rice productivity and profitability. In other words, does earlier rice transplanting imply an unacceptable trade-off at the cropping system level? To address these questions, we ran the Agricultural Production Systems sIMulator (APSIM) simulation model with historical weather data for a location in Bihar near the geographic centre of our AOI. Simulations assessed cropping system productivity, irrigation requirements and economic returns (that is, gross margin) as a function of rice transplanting date for a medium-textured soil type that is broadly representative of the study region. Gross margins were calculated using cost of cultivation data from previous studies in the region[25] and from plot-level summary data collected by the government of India (https://eands.dacnet.nic.in/Plot-Level-Summary-Data.htm). Two different rice cultivars were simulated that have similar yield potential but different growth duration: (1) a long-duration inbred variety—MTU7029 and (2) a medium-duration hybrid—Arize6444.

Table 2 | Predicting wheat productivity gains under scenarios of change

	Scenario A: Current dates	Scenario B: Wheat intervention	Scenario C: Rice intervention	Scenario D: Rice + wheat
Wheat Y_p (t ha^{-1})	3.68	3.98	4.26	4.52
Wheat YG (t ha^{-1})	0.78	1.08	1.36	1.62
Wheat YG (%)	21	27	32	36
Production gain by closing YG (t yr^{-1})	1,760,069	2,426,514	3,063,936	3,642,316
Farmgate revenue gain by closing YG (US$ yr^{-1})	393,977,547	543,155,988	685,837,890	815,303,655

Current and intervention-based sowing date projections were used to characterize wheat yield potential and yield gaps and, in turn, to assess production and revenue gains achievable by closing these gaps across the 2.25 m ha of our study area, assuming that farmers receive minimum support prices for wheat (17.35 Indian Rupees kg^{-1}) at prevailing currency exchange rates (1 US$ = 77.51 Indian Rupees as of May 2022). The yield gap (that is, untapped production potential, t ha^{-1}) more than doubles from the baseline (Scenario A) if rice and wheat interventions are jointly implemented to advance wheat planting by 21 d (Scenario D). With intensification efforts to close the yield gap, Scenario D would produce an additional 1.88 million tons of wheat with farmgate revenues increasing by more than US$421 million per annum compared with contemporary sowing date practices.

On the basis of the analysis presented in Fig. 1, a general strategy for preserving wheat yield potential is to ensure planting before 20 November, and simulation outcomes are interpreted through that lens. For the long-duration variety, rice transplanting must occur on or before 13 July, on average, to ensure timely wheat sowing. At the system level, this transplanting date also coincides with maximum simulated grain productivity and profitability (Fig. 5). Before this date, there is a broad window for rice transplanting where system-level performance is relatively high and stable across dates. After this date, productivity falls markedly, with gross margins at the system level declining by more than 25% if rice transplanting is delayed by two weeks. Reductions in economic returns occur more rapidly than yield reductions because irrigation requirements for long-duration rice increase significantly with later transplanting. Compared with long-duration rice, simulation results suggest a broader transplanting window for near-optimal systems productivity with medium-duration hybrid rice. Gross margins and grain yields are very similar between 15 June and 3 August, and transplanting medium-duration rice within this window ensures that the wheat crop can be planted on time.

Simulation results are probably broadly representative of our AOI, but subregional differences in soil properties, landscape-mediated field drainage characteristics and rainfall patterns will probably influence optimal rice transplanting dates in any given production year. Anticipated advances in soil and drainage class mapping will permit a richer set of simulations that account for these differences.

Discussion

The results of our analysis suggest that major gains in wheat productivity are achievable in the EGP if management is modified to ensure timely wheat establishment as a mechanism for climate resilience. By combining changes in rice and wheat management, greater adjustments to the annual cropping calendar are anticipated to increase wheat yield potential by an average of 0.84 t ha^{-1}, thereby providing greater scope for yield increase, food security and income generation

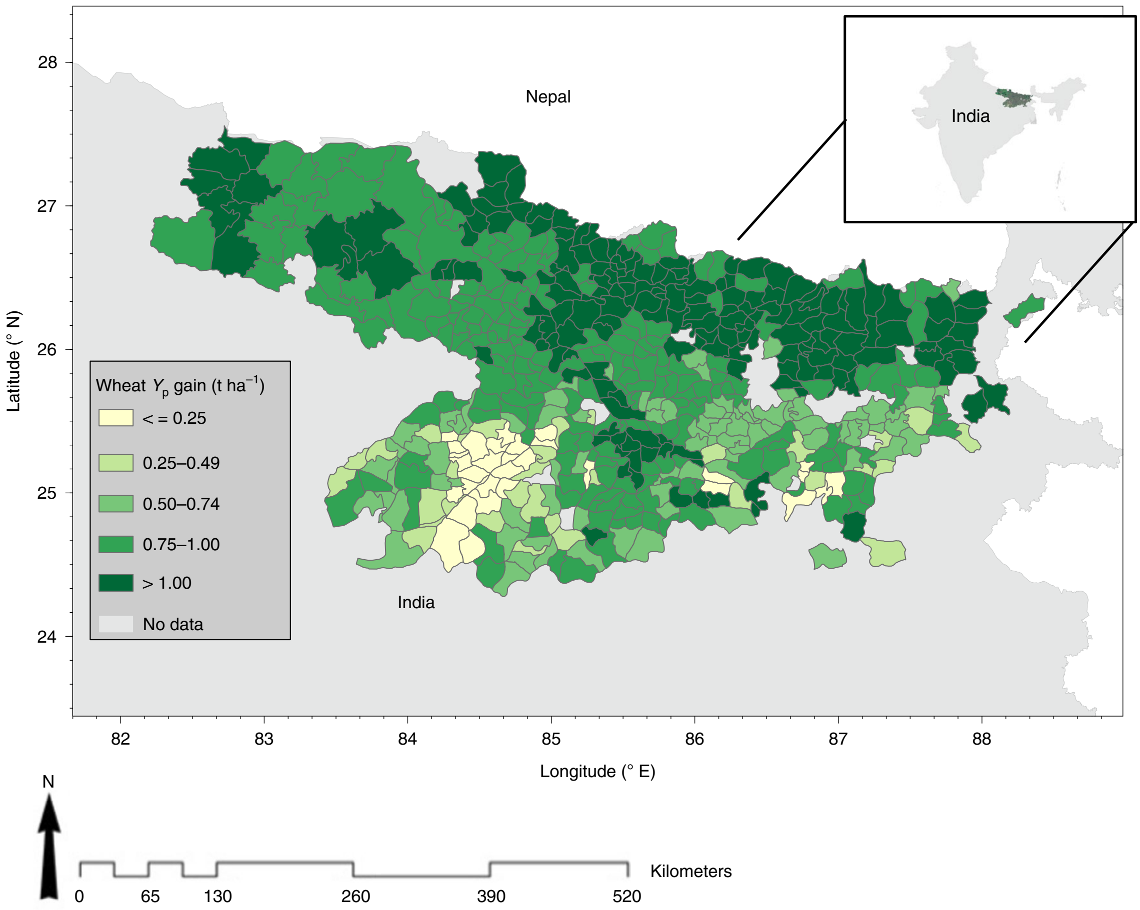

Fig. 4 | Spatial predictions of wheat yield potential gains with systems-level management interventions. Anticipated increases in wheat Y_p at the administrative block level if sowing dates are advanced by three weeks through practices that affect both the rice and wheat crops (Scenario D in Table 1). The largest gains >1 t ha^{-1} are concentrated in the northern half of the study area, whereas modest benefits are predicted in the southwest, where very late wheat sowing is common across years (Fig. 2).

in the EGP. This represents a 69% increase in the attainable wheat yield gap over a baseline estimate of 0.78 t ha^{-1}. If these gains are realized, they would transition our study region from being a net wheat importer to a important source of wheat for other food-insecure regions in South Asia[26]. This outcome aligns with the agricultural development policy ambitions established by the government of India through the National Food Security Mission and special initiatives therein, including Bringing the Green Revolution to eastern India. Transitions to timely wheat planting will probably increase system reliability by reducing interannual production variability and, crucially, there are no anticipated trade-offs with RW systems-level productivity if rice is managed in a manner to ensure timely wheat establishment. As the favourable thermal window for dry-season wheat shrinks in South Asia with progressive climate change[17], timely wheat establishment will probably assume even greater importance for yield and production reliability in the EGP[27,28].

Nevertheless, the challenge of scaling innovative management strategies to optimize the annual cropping calendar is not typically a simple task because many farmers must take several steps beyond simply *choosing* to plant earlier to implement a new time management strategy (Table 2). This is particularly true in the case of the coupled RW systems of the EGP where rice harvest date exerts strong control over the timing of wheat planting (Fig. 3). Further, there is a notable spatial dimension to the early-planting opportunity, with the northern half of our study area constituting the priority area for action (Fig. 4). There are several potential pathways towards effective time management of the RW cropping calendar that differ with respect to investment costs and other factors affecting feasibility and desirability of adoption. Here we briefly describe six of the more promising options that can be implemented independently or, in some cases, as complementary strategies that may collectively return gains in crop productivity and resilience beyond those estimated in this study through more radical adjustments to the cropping calendar. These promising options include:

Pathway 1. Many farmers currently wait for the arrival of substantial pre-monsoon rain showers before establishing rice nurseries and, thereafter, the occurrence of inundating monsoon rainfall to subsequently transplant seedlings into the main field[23]. This management approach reduces or even eliminates early irrigation requirements[29], which is a key consideration for the many farmers in eastern India that rely on shallow tube wells and expensive-to-operate diesel pump sets. Although initial cash investment costs are reduced, these strategies also delay rice crop establishment and the timing of harvest[23]. Rapidly expanding rural electrification programmes may be a game changer for earlier rice establishment[30], especially if less expensive energy sources are combined with reliable planting date advisories that take advantage of the increasing skill of sub-seasonal monsoon forecasts in South Asia[31].

Pathway 2. Even with cheaper energy and robust agro-advisories, many farmers may continue to wait for the arrival of pre-monsoon rains to establish rice nurseries. In practice, this is a form of risk management that prevents rice yield reductions emanating from

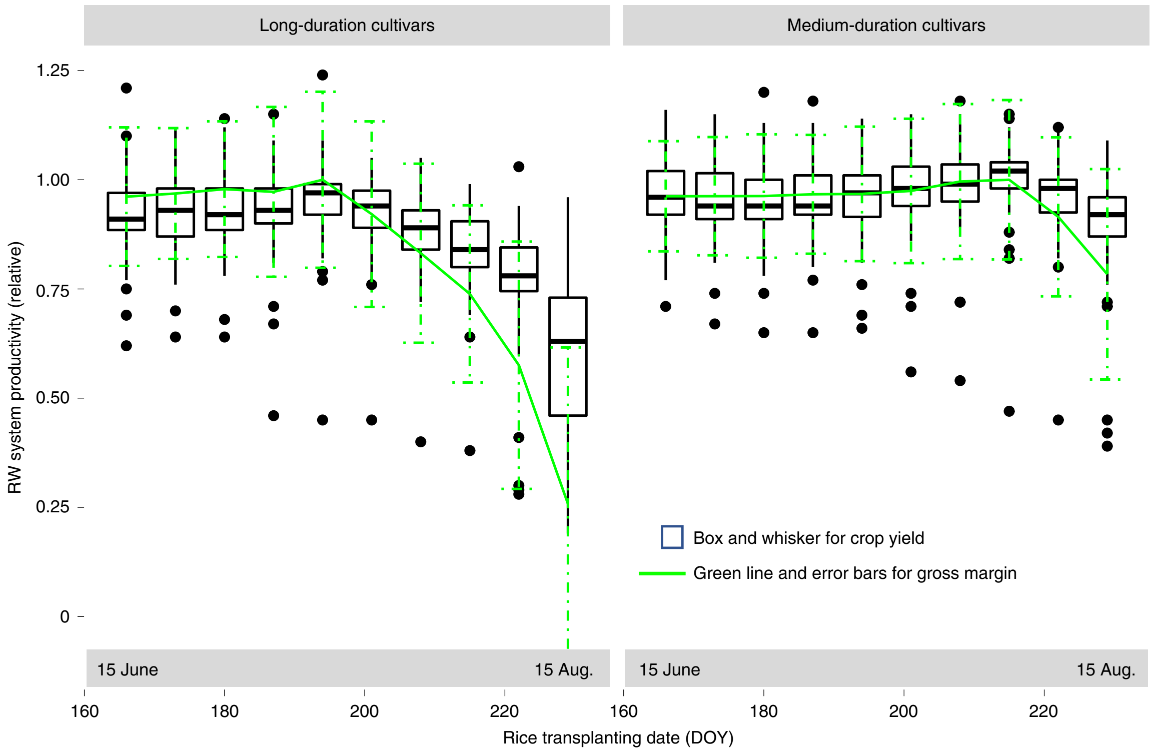

Fig. 5 | RW system-level productivity and rice transplanting date. Substantial changes in the timing of wheat sowing require management innovations to the rice phase of the annual crop rotation. Dynamic simulation with the APSIM model was used to assess potential trade-offs between rice transplanting date and RW systems-level productivity for both long-duration (modern inbred) and medium-duration (hybrid) rice cultivars. Yields are calculated in rice equivalent terms and profitability estimated through gross margins; both are expressed relative to the highest mean value across all transplanting dates by rice variety combinations. Box plots show yield distributions at 7 d intervals with the line within each box representing the median and the lower and upper boundaries of the box indicating the first and third quartiles, respectively. Error bars (whiskers) represent 1.5× the interquartile range, with data points above or below this shown as outliers. Systems-level gross margin is depicted by the green line with error bars (±1 SD from the mean) representing interannual variation. For systems with long-duration rice, simulation results suggest that transplanting on or before 13 July (DOY 201) is essential for ensuring high yield and profitability outcomes. A broader window of opportunity exists for RW systems planting medium-duration rice, with high and stable productivity achievable through early August.

use of older seedlings in case the inundating rains that facilitate rice transplanting are delayed. Through social and small business enterprises, there is scope for the production and sale of ‘staggered’ nurseries that seek to provide appropriately aged seedlings to farmers to plant whenever monsoon showers commence. In many circumstances, this may accelerate planting by two or more weeks while helping to preserve rice yield potential by avoiding the use of old seedlings.

Pathway 3. Directly sown rice (DSR) facilitates early rice establishment because it requires less water for establishment compared with transplanted rice and is typically sown in drained soil conditions before the onset of the monsoon[32]. Further, DSR matures 8–10 d earlier than a transplanted rice crop due to the absence of transplant shock[32]. On the basis of long-term simulations, the optimum time for sowing DSR is within the first half of June[29]. Even with long-duration rice varieties, DSR sown by mid-June will be harvested by late October, leaving ample time to prepare the field and sow the wheat crop on time.

Pathway 4. In this study, simulation results suggest that long-duration rice (that is, MTU7029) must be transplanted on or before 13 July (Fig. 5) to ensure timely wheat planting and high levels of RW systems productivity. Results also suggest considerably more ‘room to manoeuvre’ if farmers transition to medium-duration hybrid rice (for example, Arize6444) that can be planted until early August while maintaining high yields and profitability at the systems level. These results are consistent with recent field trials conducted by the Cereal Systems Initiative for South Asia (CSISA) project and scientists from the Indian Council for Agricultural Research in Patna, Bihar.

Pathway 5. On the basis of survey data for the 2018 wheat harvest, the average time gap between rice harvest and wheat planting is 15 d. With traditional practices (implemented by ~45% of the farmers in our AOI with strong geographic differences), rice is hand-harvested and left in the main field to sun dry for several days before it is manually threshed. With mechanical threshing, rice can be removed from the field at the time of harvest, saving approximately 7 d of drying time. Combine harvesting also provides an efficient approach to reducing turn-around time between crops but is often associated with crop residue burning with detrimental effects on health and the environment[33].

Pathway 6. Prevailing tillage-based wheat establishment practices require repeated tillage passes that can take a week to complete, depending on soil conditions. Zero-till systems permit farmers to forgo these steps and to plant directly into untilled soil, ostensibly saving time[34]. On the basis of the same sample of farm households that we use for the current study, Keil et al.[35] estimated a 19% yield increase due to the use of zero till in wheat (equivalent to 498 kg ha^{-1}) but did not find systematic differences in the cropping calendar based on differences in crop establishment methods in the EGP. Further survey work is required to understand if increased awareness of the value of timely wheat establishment changes planting date practices in the EGP when technologies such as zero till are broadly available.

Each of these adaptation pathways has its own risks, investment requirements and scaling considerations. Broadly speaking, technology adoption constraints can be related to insufficient awareness of an innovation, limited or unaffordable access, a heterogeneous range of expected benefits or institutional and policy hurdles (as an example from the South Asia region, see Krishna et al.[36] for a review of constraints to the diffusion of zero till). For the mechanization approaches described above, adoption in the EGP is limited by the fact that tractor ownership is not economically tenable for most smallholder farmers. In our random sample of farm households in Bihar, only 8% of households owned a tractor. Hence, for most of farmers in the area, the use of mechanization technologies to facilitate timely wheat establishment and other management goals is not only a household-level decision but rather one that is conditioned by access to service providers[37].

The same adoption caveats hold for innovations such as medium-duration hybrid rice where there is a clear business case for the private sector along with readily observed yield and profitability gains for farmers[38]. From our survey data, 49% of the households in Samastipur District (Bihar) grew hybrid rice in 2013, and the share increased to 88% in 2016. In other districts, however, the cultivation of hybrid rice is entirely absent, probably reflecting a combination of tractable and binding constraints, such as poor market access or persistent flooding that favour the cultivation of long-duration rice varieties. Similar spatial dependence is evident with the spread of combine harvesting which, at present, is practised only by an estimated 10% of the rice farmers in our study area but with a strong degree of geographic heterogeneity and relatively higher levels of adoption in the western third of our study area.

To accelerate transitions to timely wheat establishment, three inter-dependent approaches are probably required. First, the expected yield, resilience and profitability gains of different innovations need to be contextualized and articulated at the cropping system level. Much of the applied agricultural research portfolio in South Asia retains a strong single-commodity focus, as does much of the adaptation literature that often highlights crop-specific response options for addressing progressive climate change[39]. Institutional barriers to cross-commodity research have long been recognized in the South Asia context, and multi-stakeholder partnerships such as the Rice–Wheat Consortium and the Cereal Systems Initiative for South Asia were devised to address challenges at the cropping system level. More progress in this direction is required. Second, evidence-based opportunity targeting for specific adaptation pathways will ensure that proposed innovations are responsive to variations in biophysical, social and economic factors that, in aggregate, determine the suitability and enabling environment that permit innovations to scale in different contexts[40,41]. Developing and mapping household typologies offers a pragmatic way to systematize these insights[42] and can be used conjunctively with ex ante assessment frameworks such as the ADOPT tool to anticipate patterns of adoption and to prioritize interventions accordingly[43]. Lastly, it is increasingly recognized that sustainable development rarely happens through technologies or knowledge provision alone. Almost all the priority development pathways for effective cropping calendar management in the RW system entail changes to markets[38,44] or social organization[23], and placing more emphasis on socio-technical innovation bundles to accelerate change processes is imperative[45].

In summary, for our study region covering 2.25 million ha of the RW cropping system in eastern India, current cropping calendar management erodes wheat yield potential, climate resilience and the scope for sustainable intensification. Nevertheless, transformative productivity and livelihood gains from earlier wheat planting will be possible only if adjustments are made to rice management, including earlier transplanting and the cultivation of shorter-duration crop cultivars. There are, however, notable geographic differences and multiple pathways for supporting change that must be prioritized and targeted to accelerate the process of adaptation. As the duration of the cool winter period is shortened by progressive climate change, the importance of timely wheat planting is likely to increase significantly. Steps taken to 'keep time' through better management of the cropping calendar will pay dividends for food security, profitability and resilience now and in the years ahead.

Methods

The research conducted herein complies with standards established by the Research Ethics Committee of the International Maize and Wheat Improvement Center as described in policy number DDG-POL-04–2019.

The study area in eastern India is composed of Bihar state and seven adjacent districts in Uttar Pradesh state (Supplementary Fig. 1), encompassing approximately 2.25 million ha of the RW cropping system. The districts of Bihar fall into four major agro-climatic zones (ACZs): zone I (northern West), zone II (northern East), zone IIIA (southern East) and zone IIIB (southern West), while the districts of Uttar Pradesh fall into zone IV (Fig. 1). The climate in the study's AOI is classified as humid subtropical, with distinct wet and dry seasons (Supplementary Fig. 2). Rice is generally transplanted from early July to mid-August, a period that coincides with the heaviest monsoon rainfall. Wheat follows rice and is sown between early November and late December with harvest extending from late March through April. Spring wheat varieties are primary cultivated in this region during the winter period, that is, varieties that do not have big vernalization requirements.

Household surveys to characterize planting date decisions. To elicit information on decision-making processes for wheat planting dates, detailed household surveys were deployed using a cluster sampling approach from 40 randomly selected villages across six districts of Bihar. A second random draw was done to select farm households within each village with a total of 1,000 surveys conducted from August to October 2013. The districts were Vaishali, Samastipur and Begusarai in ACZ zone I, Lakhisarai in zone IIIA, and Bhojpur and Buxar in zone IIIB. From May to July 2016, 96% of the sample households were revisited and the same information elicited for the seasons 2013–2014 through 2015–2016. A total of 5,766 site-year observations for crop establishment and harvesting times were collected by repeated sampling from 961 farm households, spanning the six-year period 2010 through 2015. The full dataset and description of the survey instrument can be accessed via Dataverse[46].

Landscape diagnostic surveys for determinants of wheat productivity. Data on wheat yields, production practices and site characteristics were collected across Bihar state and adjacent districts in Uttar Pradesh for five wheat growing seasons (2012–2013 to 2016–2017). The sampling strategy was purposive with farmers associated with the Cereal Systems Initiative for South Asia (www.csisa.org) and their neighbours targeted for the survey with a total number of 6,216 site years, with n ranging from 429 to 1,074 for each year. Crop cuts were conducted at the time of harvest in early April with three 2×1 m plots within each field assessed for biomass and grain, the latter reported at 14% moisture content.

For the 2017–2018 wheat growing season, the sampling strategy and survey instrument were revised to achieve a representative sample of wheat growing farmers in the area of interest coupled with a more comprehensive set of questions[47]. A total of 7,648 individual fields were characterized in collaboration with the Indian Council of Agricultural Research. Sites were selected through a two-stage process that first randomly identified 30 rural villages per district and then, within each village, randomly selected seven farm households based on voting rolls. For selecting villages, a 'probability proportionate to size' method of random sampling was employed with the sampling frame constrained to villages with more than 30 and less than 5,000 households. In all landscape diagnostic surveys (LDSs), the largest wheat plot was characterized for site attributes (for example, field area, landscape position, soil texture class), agronomic production practices (for example, fertilizer and agro-chemical input use, planting and harvest dates, irrigation practices, crop variety, crop establishment method), socio-economic factors (for example, land tenure, household and landholdings size, marketed crop share and sale price, total income share from agriculture) and self-reported grain yield. The full dataset and description of the survey instrument can be accessed via Dataverse[48]. For the 2017–2018 data, digital soil mapping predictions for soil chemical properties (nutrient concentrations, pH, organic carbon) were also estimated for each field.

In addition to standard summary statistics, two additional analytical approaches were used with the LDS survey data. First, boundary line analysis was used to establish wheat yield potential (Y_p) as it varies by planting date by fitting a function to the outer edge of the yield (y axis) and sowing date (x axis) data

Table 3 | Scenarios of wheat sowing date change and descriptions of how they can be achieved

Scenario	Wheat planting	Description
Scenario A Mean wheat planting date	No adjustment	Counterfactual that serves as the baseline for constructing change scenarios and the point of reference for estimating gains in Y_p. Estimated from MODIS data for the period from 2003–2017.
Scenario B Wheat interventions	Potential 7 d advancement	Through extension messaging and mechanization, wheat planting is advanced by a week with no changes in rice planting practices, except in the estimated 11% of fields that remain too wet to be planted earlier.
Scenario C Rice interventions	Potential 14 d advancement	Through direct sowing (DSR), earlier rice transplanting or the adoption of shorter-duration hybrids, farmers can advance rice harvest by two weeks, translating into a commensurate advancement in wheat planting dates except in the estimated 11% of fields that remain too wet to be planted earlier. Earlier rice transplanting is achieved through measures such as improved agro-advisories, judicious use of early irrigation and mechanization to address labour bottlenecks.
Scenario D Wheat *and* rice interventions	Potential 21 d advancement	Rice and wheat interventions are implemented in tandem as described above.

cloud. This approach assumes that all other productivity-influencing factors have a modest effect on yield at the boundary line such that the effect of planting date on Y_p is isolated[49]. We also assume that the highest-yielding farmers in the region are operating at or near the biological yield frontier where water, nutrients and other management factors do not limit crop performance[50]. The outer edge was defined by first binning each year's survey data into 5 d intervals and then identifying the 90% percentile yield of the data distribution within each bin. Thereafter, piecewise linear regression was used to model a generalized boundary line for the six years of data with the 'Segmented' package within the R statistical computing environment (R version 4.1.2). Interannual variability of Y_p was assessed by characterizing the standard deviation of the mean for each 5 d period.

To characterize the overall importance of contemporary wheat sowing date distributions to yield outcomes in comparison to other soil and agronomic factors, machine learning analytics (that is, Random Forest, implemented as 'boosted forest' in JMP Pro v14 statistical software) were used to develop predictive models for yield and to rank factors in their order of importance through recursive permutation. Because the LDS survey design changed in 2017–2018, two separate models were constructed.

Satellite-based crop assessments. Total wheat area and crop establishment dates were derived from MODIS satellite data for a 16-year period (2002 to 2017 wheat harvest years). By combining 16 d composite vegetation indices from the Terra (MOD13Q1) and Aqua (MYD13Q1) satellites at 250 m spatial resolution, time series estimates of Enhanced Vegetation Index (EVI) were analysed at 8 d intervals for the entire AOI during the winter cropping cycle. Thereafter, vegetation growth functions were derived for each pixel from the EVI data using the TIMESAT software package and the Savitzky–Golay filter[51]. Subsequently, these functions were used to estimate phenological parameters, including start of the season (that is, sowing), end of the season (that is, physiological maturity) and cropping duration.

Satellites cannot reliably detect the early stages of crop growth, hence correction factors must be used to estimate true sowing dates. By comparing satellite EVI values with ground truth data from the LDS surveys at six different locations, we estimated that wheat EVI values reached 15% of their maximum approximately three weeks after sowing, a result consistent with Lobell et al.[52]. Consequently, a three-week adjustment was applied to every pixel from the date when 15% max EVI was reached to estimate the true timing of crop establishment. To estimate physiological maturity, we assessed the descending limb of the EVI growth curve and determined the date when EVI values first reached their seasonal minimum. Crop duration was calculated as the difference in days between sowing and maturity.

An area mask was also developed to segregate wheat pixels from other vegetation types. A multi-stage process was used for this purpose. First, maximum EVI criteria were applied to the winter cropping season based on Wardlow et al.[53] and Schulthess et al.[54] to separate intensified crops, such as wheat, from winter fallow and low-yielding pulse crops, such as lentil. Then, the seasonality of crop growth was used to remove areas with natural vegetation, such as forests. Next, known planting and harvest date ranges for wheat in the target region were used to segregate wheat from other high-yielding winter crop types such as maize and sugar cane. We verified model performance against 201 ground points that were approximately equally split between wheat and non-wheat crops and achieved an overall map accuracy of 86% for wheat versus non-wheat crop type classification.

Increasing wheat Y_p through sowing date adjustments. The boundary line analysis method provides a data-driven approach for estimating attainable wheat Y_p as a function of planting date. To assess likely changes in yield potential that result from plausible planting date modifications, we applied this model first with the longer-term mean planting date for every 250 m wheat pixel in our AOI (that is, satellite-derived 'Scenario A') and then with three different scenarios of change that reflect agronomically realistic pathways for adjusting wheat planting dates based on expert knowledge from the region. Scenarios tested include wheat-specific interventions ('Scenario B'), interventions that target rice ('Scenario C') and interventions that influence both rice and wheat phases of the cropping cycle ('Scenario D') (Table 3). On the basis of the LDS survey responses from 2018 to the question 'if wheat is usually planted late, what is the reason?', we estimated that 11% of the fields in our AOI are too wet to plant earlier in most years, and these fields represent the lagging tail of the contemporary planting date distribution. In our scenario analysis, poor drainage is treated as a binding constraint, and all fields with mean planting dates on or after 25 December (that is, approximately 11% of the planting date distribution) are assumed to be fixed. On the basis of survey data, we also assumed that wheat will not be planted before 27 October.

These scenarios were used to develop a spatial opportunity assessment that characterizes wheat yield potential in our AOI as a set of values defined by a distribution of sowing dates. This represents a departure from most yield gap assessment studies that treat planting date as a single (usually optimized) attribute of the cropping system that is applied across an AOI, rather than a distribution that reflects current farmer practice or a modification thereof[55]. Modelled gains in wheat yield potential are further contextualized with reference to yield gaps by calculating the difference between yield potential and actual productivity levels ($YG = Y_p - Y_{actual}$). For our purposes, we use survey data from 2018 to estimate average Y_{actual} within the study region as 2.9 t ha^{-1}.

Cropping rotation simulations. In tightly sequenced crops such as those in the RW system, planting date adjustments must be assessed at the cropping systems level from the perspective of practical feasibility (that is, *can this be done?*) but also to identify management strategies that optimize performance by minimizing trade-offs. To this end, APSIM v7.09 was used to simulate a range of coupled RW planting date scenarios to assess implications for aggregate crop yields, interannual yield stability, irrigation water requirements and economic productivity. Simulations were conducted for a single site in Patna, Bihar, that is situated near the centre of our broader areas of interest; variations in subregional climate and soil factors are not considered in our analysis.

APSIM is a flexible modelling framework that enables a variety of sub-models of the soil–plant–atmosphere system to be linked to simulate agricultural system performance[56]. Sub-models include crop-specific dynamic growth models and different options for representing soil processes such as water fluxes and the N balance. In this study, we use the WHEAT module[57] for simulating wheat and the ORYZA module[58] for rice. APSIM was calibrated with crop growth and soil data from an Indian Council of Agricultural Research experimental site in Patna, Bihar. The most common crop cultivars grown in the region (MTU7029 and Arize6444 for rice, PBW343 for wheat) and silt loam soil characteristics were used for model parameterization. This soil type is broadly representative of many of the alluvial soils in the EGP with respect to physical and chemical properties[59]. Depth-wise soil physical properties are presented in Supplementary Table 2. Temporal changes in hydraulic conductivity are used to capture the shift between lowly permeable 'puddled' soil during the rice season to dry-land soils with higher rates of internal drainage during the wheat season. APSIM performs well in simulating RW systems under contrasting production environments across Asia[29,60], and these prior studies provide the basis for its application in our work without additional model verification.

The calibrated model was used to evaluate the performance of the RW rotation under different rice transplanting dates starting from June to mid-September at 7 d increments with both longer-duration (MTU7029, 155 d—improved inbred) and medium-duration (Arize6444, 135 d—hybrid) rice cultivars. APSIM genetic coefficients for both rice varieties are presented in Supplementary Table 3. Simulations were driven with 43 years (1970–2013) of daily weather data with management factors set to reflect best agronomic practices for seedling age, planting densities and fertilization (Balwinder-Singh et al.[29]). The rice crop was irrigated daily as needed to maintain continuous ponding (flood depth of 50 mm) for the first two weeks after transplanting. Thereafter, the crop was irrigated 3 d after disappearance of ponded water. The wheat cultivar PBW343 was sown 15 d after rice harvesting and was irrigated whenever soil water in the top 60 cm of the soil profile decreased to 50% of plant available water content (50% soil water deficit). Wheat genetic coefficients are presented in Supplementary Table 4. By applying full irrigation and best agronomic management practices, soil and water limitations to crop growth are minimized in our simulations.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Source data files provide the raw data used to produce all figures. Access to additional ancillary data and, where appropriate, survey code books are available. *Landscape diagnostic surveys*: production practice, site characterization and yield data for the 2018 wheat crop are available from the CSISA data repository, https://hdl.handle.net/11529/10548507. Data from previous survey years (2013–2017 wheat harvest years) and digital soil maps for the study's AOI are available from the corresponding author upon request. *Household surveys*: data used to understand decision factors and biophysical constraints to timely wheat planting are available from the CSISA data repository, https://hdl.handle.net/11529/10885. *Spatial data*: MODIS EVI data were acquired from the US National Aeronautics and Space Administration Land Data Products and Services portal, https://lpdaac.usgs.gov/products/mod13q1v006/. Derived estimates of wheat sowing dates are provided as source data for Fig. 4. Additional TIMESAT-based predictions of crop sowing, harvest and growth duration estimated for every MODIS pixel in our AOI is available upon request from the corresponding author. Political boundaries depicted in our maps are freely distributed for academic and non-commercial use by GADM (www.gadm.org). *APSIM simulation data*: The model input parameters for crop and soil attributes are provided in the Supplementary Information. Scenario output data (that is, RW productivity and resource use) from long-term simulations are provided as source data for Fig. 5. Additional simulation output data are available on request from the corresponding author. Source data are provided with this paper.

Received: 23 June 2021; Accepted: 12 June 2022;

References

1. Chatrath, R., Mishra, B., Ortiz Ferrara, G., Singh, S. K. & Joshi, A. K. Challenges to wheat production in South Asia. *Euphytica* **157**, 447–456 (2007).
2. Ramadas, S., Kiran Kumar, T. M. & Singh, G. P. in *Recent Advances in Grain Crops Research* (eds Shah, F. et al.) Ch. 6 (IntechOpen, 2020).
3. Singh, S., Kumar, A., Ramadas, S., Khippal, A. & Singh, G. P. *All India Coordinated Research Project (AICRP) on Wheat and Barley Progress Report 2019–20 Social Sciences* (ICAR, 2020); https://doi.org/10.13140/RG.2.2.12852.88967
4. *The State of the World's Land and Water Resources: Managing Systems at Risk* (United Nations, 2011).
5. Timsina, J. & Connor, D. J. Productivity and management of rice–wheat cropping systems: issues and challenges. *Field Crops Res.* **69**, 93–132 (2001).
6. Jain, M. et al. Using satellite data to identify the causes of and potential solutions for yield gaps in India's Wheat Belt. *Environ. Res. Lett.* **12**, 094011 (2017).
7. Humphreys, E., Kukal, S. S., Christen, E. W., Hira, G. S. & Sharma, R. K. Halting the groundwater decline in North-West India—which crop technologies will be winners?. *Adv. Agron.* **109**, 155–217 (2010).
8. Ladha, J. et al. in *Integrated Crop and Resource Management in the Rice–Wheat System of South Asia.* (eds Ladha, J. K. et al.) 69–108 (IRRI/CABI Publishers, 2009).
9. Kumar, V. et al. Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. *Agric. Ecosyst. Environ.* **252**, 132–147 (2018).
10. Balwinder-Singh, McDonald, A. J., Srivastava, A. K. & Gerard, B. Tradeoffs between groundwater conservation and air pollution from agricultural fires in northwest India. *Nat. Sustain.* **2**, 580–583 (2019).
11. Pathak, H. et al. Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Res.* **80**, 223–234 (2003).
12. Erenstein, O., Malik, R. K. & Singh, S. *Adoption and Impacts of Zero-Tillage in the Rice–Wheat Zone of Irrigated Haryana, India* (RWC, CIMMYT, 2007).
13. Ladha, J. K. et al. How extensive are yield declines in long-term rice–wheat experiments in Asia? *Field Crops Res.* **81**, 159–180 (2003).
14. Park, A., Davis, A. & McDonald, A. Priorities for wheat intensification in the Eastern Indo-Gangetic Plains. *Glob. Food Sec.* **17**, 1–8 (2018).
15. Farooq, M., Bramley, H., Palta, J. A. & Siddique, K. H. M. Heat stress in wheat during reproductive and grain-filling phases. *Crit. Rev. Plant Sci.* **30**, 491–507 (2011).
16. Akter, N. & Islam, M. R. Heat stress effects and management in wheat. A review. *Agron. Sustain. Dev.* https://doi.org/10.1007/s13593-017-0443-9 (2017).
17. Ortiz, R. et al. Climate change: can wheat beat the heat? *Agric. Ecosyst. Environ.* **126**, 46–58 (2008).
18. Hunt, J. R. et al. Early sowing systems can boost Australian wheat yields despite recent climate change. *Nat. Clim. Change* **9**, 244–247 (2019).
19. Ortiz-Monasterio, R. J. I., Dhillon, S. S. & Fischer, R. A. Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. *Field Crops Res.* **37**, 169–184 (1994).
20. Newport, D. et al. Factors constraining timely sowing of wheat as an adaptation to climate change in eastern India. *Weather Clim. Soc.* **12**, 515–528 (2020).
21. Guilpart, N., Grassini, P., Sadras, V. O., Timsina, J. & Cassman, K. G. Estimating yield gaps at the cropping system level. *Field Crops Res.* **206**, 21–32 (2017).
22. Lal, P. N. & Mitchell, T. in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* (eds Field, C. B. et al.) Ch. 6 (IPCC, 2012).
23. Urfels, A. et al. Social-ecological analysis of timely rice planting in Eastern India. *Agron. Sustain. Dev.* **41**, 14 (2021).
24. Singh, M. et al. Intercomparison of crop establishment methods for improving yield and profitability in the rice–wheat system of Eastern India. *Field Crops Res.* **250**, 107776 (2020).
25. Gathala, M. K. et al. Improving smallholder farmers' gross margins and labor-use efficiency across a range of cropping systems in the Eastern Gangetic Plains. *World Dev.* **138**, 105266 (2021).
26. Paulsen, J. et al. Wheat value chain: Bihar. *Gates Open Research 2019* **3**, 593 (2012); https://doi.org/10.21955/gatesopenres.1115558.1
27. Asseng, S. et al. Rising temperatures reduce global wheat production. *Nat. Clim. Change* **5**, 143–147 (2015).
28. Lobell, D. B., Ortiz-Monasterio, J. I., Sibley, A. M. & Sohu, V. S. Satellite detection of earlier wheat sowing in India and implications for yield trends. *Agric. Syst.* **115**, 137–143 (2013).
29. Balwinder-Singh et al. Taking the climate risk out of transplanted and direct seeded rice: insights from dynamic simulation in Eastern India. *Field Crops Res.* **239**, 92–103 (2019).
30. Kishore, A. *The Changing Energy: Irrigation Nexus in Eastern India. ACIAR SDIP Foresight Program: Status Report* (International Food Policy Research Institute (IFPRI), 2019); https://doi.org/10.2499/p15738coll2.133588
31. Robertson, A. W. et al. Subseasonal forecasts of the 2018 Indian summer monsoon over Bihar. *J. Geophys. Res. Atmos.* **124**, 13861–13875 (2019).
32. Kumar, V. & Ladha, J. K. Direct seeding of rice: recent developments and future research needs. *Adv. Agron.* **111**, 297–413 (2011).
33. Shyamsundar, P. et al. Fields on fire: alternatives to crop residue burning in India. *Science* **365**, 536–538 (2019).
34. Erenstein, O. & Farooq, U. A survey of factors associated with the adoption of zero tillage wheat in the irrigated plains of South Asia. *Exp. Agric.* **45**, 133–147 (2009).
35. Keil, A., D'souza, A. & McDonald, A. Zero-tillage as a pathway for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: does it work in farmers' fields? *Food Secur.* **7**, 983–1001 (2015).
36. Krishna, V. V., Keil, A., Aravindakshan, S. & Meena, M. in *Achieving Sustainable Cultivation of Wheat* Vol. 2 (ed Langridge, P.) Ch. 3, 1–62 (Burleigh Dodds Science Publishing, 2017).
37. Keil, A., D'Souza, A. & McDonald, A. Growing the service economy for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: lessons from custom hiring services for zero-tillage. *Food Secur.* **8**, 1011–1028 (2016).
38. Spielman, D. J., Ward, P. S., Kolady, D. E. & Ar-Rashid, H. Public incentives, private investment, and outlooks for hybrid rice in Bangladesh and India. *Appl. Econ. Perspect. Policy* **39**, 154–176 (2017).
39. Dubey, R. et al. Impact of terminal heat stress on wheat yield in India and options for adaptation. *Agric. Syst.* **181**, 102826 (2020).
40. Coe, R., Sinclair, F. & Barrios, E. Scaling up agroforestry requires research 'in' rather than 'for' development. *Curr. Opin. Environ. Sustain.* **6**, 73–77 (2014).
41. Glover, D., Sumberg, J., Ton, G., Andersson, J. & Badstue, L. Rethinking technological change in smallholder agriculture. *Outlook Agric.* **48**, 169–180 (2019).
42. Lopez-Ridaura, S. et al. Climate smart agriculture, farm household typologies and food security: an ex-ante assessment from Eastern India. *Agric. Syst.* **159**, 1–13 (2018).
43. Kuehne, G. et al. Predicting farmer uptake of new agricultural practices: a tool for research, extension and policy. *Agric. Syst.* **156**, 115–125 (2017).
44. Keil, A., Mitra, A., Srivastava, A. K. & McDonald, A. Social inclusion increases with time for zero-tillage wheat in the Eastern Indo-Gangetic Plains. *World Dev.* **123**, 104582 (2019).
45. Barrett, C. B. et al. Bundling innovations to transform agri-food systems. *Nat. Sustain.* **3**, 974–976 (2020).
46. Keil, A. & Michalski, J. *Replication Data for: Zero Tillage Adoption and Its Welfare Impacts at the Farm Household Level* (CIMMYT Research Data and Software Repository Network, 2017); https://data.cimmyt.org/dataset.xhtml?persistentId=hdl:11529/10885

47. Singh, A. K. et al. *New Frontiers in Agricultural Extension—Volume 1* (CIMMYT, 2019).
48. Ajay, A., Craufurd, P., Sharma, S. & Al., E. Landscape diagnostic survey data of wheat production practices and yield of 2018 from eastern India. *CIMMYT Research Data and Software Repository Network* https://hdl.handle.net/11529/10548507 (2020).
49. Hajjarpoor, A. et al. Using boundary line analysis to assess the on-farm crop yield gap of wheat. *Field Crops Res.* **225**, 64–73 (2018).
50. van Ittersum, M. K. et al. Yield gap analysis with local to global relevance—a review. *Field Crops Res.* **143**, 4–17 (2013).
51. Jönsson, P. & Eklundh, L. TIMESAT—a program for analyzing time-series of satellite sensor data. *Comput. Geosci.* **30**, 833–845 (2004).
52. Lobell, D. B., Sibley, A. & Ivan Ortiz-Monasterio, J. Extreme heat effects on wheat senescence in India. *Nat. Clim. Change* **2**, 186–189 (2012).
53. Wardlow, B. D., Egbert, S. L. & Kastens, J. H. Analysis of time-series MODIS 250 m vegetation index data for crop classification in the U.S. Central Great Plains. *Remote Sens. Environ.* **108**, 290–310 (2007).
54. Schulthess, U., Timsina, J., Herrera, J. M. & McDonald, A. Mapping field-scale yield gaps for maize: an example from Bangladesh. *Field Crops Res.* **143**, 151–156 (2013).
55. Van Ittersum, M. K. et al. Yield gap analysis with local to global relevance—a review. *Field Crops Res.* **143**, 4–17 (2013).
56. Holzworth, D. P. et al. APSIM—evolution towards a new generation of agricultural systems simulation. *Environ. Model. Softw.* **62**, 327–350 (2014).
57. Asseng, S. et al. Performance of the APSIM-wheat model in Western Australia. *Field Crops Res.* **57**, 163–179 (1998).
58. Bouman, B. A. M. & Van Laar, H. H. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. *Agric. Syst.* **87**, 249–273 (2006).
59. Shangguan, W., Dai, Y., Duan, Q., Liu, B. & Yuan, H. A global soil data set for earth system modeling. *J. Adv. Model. Earth Syst.* **6**, 249–263 (2014).
60. Gaydon, D. S. et al. Evaluation of the APSIM model in cropping systems of Asia. *Field Crops Res.* **204**, 52–75 (2017).

Acknowledgements

This work was made possible by long-term funding to the author team from the Bill and Melinda Gates Foundation (BMGF grant numbers OPP1052535 and OPP1133205) and the US Agency for International Development (USAID grant number BFS-G-11-00002) to the Cereal Systems Initiative for South Asia. CSISA is an eco-regional initiative to support sustainable agricultural development that has been implemented by a consortium of national and international partners in South Asia since 2009. This study is built upon the generosity and survey participation of thousands of smallholder farmers in Bihar and Uttar Pradesh, India. These surveys have been implemented at scale through the skilled and diligent work of CSISA's field scientists in collaboration with scientists from the Indian Council of Agricultural Research (ICAR) and the Krishi Vigyan Kendra (KVK) system. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of BMGF or USAID.

Author contributions

A.J.M., B.-S., A. Keil. and A.S. conceptualized, designed and implemented the study, conducted analyses and drafted the first version of the manuscript. P.C., A. Kishore, V.K., G.P., S.S., A.K.S., R.K.S. and R.K.M. reviewed and revised the manuscript, including the discussion and interpretation of the results.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-022-00549-0.

Correspondence and requests for materials should be addressed to Balwinder-Singh.

Peer review information *Nature Food* thanks Xiaogang Yin, Beibei Liu and Tek Sapkota for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

nature research

Corresponding author(s): Balwinder Singh

Last updated by author(s): May 31, 2022

Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Open data kit ('ODK') for building and implementing 'landscape diagnostic' field surveys; Survey Bee for building and implementing household socio-economic surveys
Data analysis	JMP Pro 14 for machine learning analytics; Segmented package in R for piece-wise linear regression; ArcGIS Pro for spatial analysis; TIMESAT for time-series analysis of satellite data; APSIM v7.09 for cropping system simulations

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

Data availability statement included in manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	Since the two types of surveys implemented in our study were observational in nature, sample size calculations to determine treatment effects were irrelevant and not captured. Rather, surveys were designed to adequately characterize on-farm variation within our area of interest given the time and financial resources of the projects. For the more intensive household surveys, a cluster sampling approach was used to randomly select 40 villages across six districts. A second random draw was done to select farm households within each village (n = 1,000 households). For the 'lighter' landscape diagnostic surveys, a total of 7,648 individual farmer fields were characterized in 2018. Sites were selected through a two-stage process that first randomly identified 30 rural villages per district and then, within each village, randomly selected 7 farm households based on voting rolls. In previous years (2013 - 2017), sampling for landscape diagnostics was purposive, with a focus on farmers that were engaged with the CSISA project and their neighbors.
Data exclusions	None
Replication	Observational studies such as ours are always limited by underlying data distributions including, perhaps most importantly interactions with the climate systems that can strongly influence the importance of factors such as crop planting date to crop yield, resilience, and resource use efficiencies. In order to understand the 'representativeness' of insights derived from field surveys (i.e. are they reproducible in the long-term), we used a simulation approach driven by long-term weather data to explore the impact of RW planting dates across climate years.
Randomization	Experimental groups were not formed in this study
Blinding	The surveys conducted in this study (household, landscape diagnostic) were observational in nature; no treatments were imposed, hence blinding was not relevant.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☐	☒	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	Household and landscape diagnostic surveys relied on farmer-respondents to participate in our study. The characteristics of the respondents varied widely by age, educational background, gender, and social class. If a farm household consented to participate, the surveyed individual was either the self-identified 'head of household' or, alternatively, the person most responsible for agricultural management.
Recruitment	Aside from the purposive sampling for cropping system characterization in the early years of the study among farmers associated with the CSISA project (and their neighbors...), both the household and landscape diagnostic surveys relied on a geographically-stratified random sampling approach. Hence, there was no a priori selection bias. If a targeted household did not grant informed consent to participate in the survey, the next household from the randomly-drawn sample list was approached until the intended number of respondents per location was reached.

Ethics oversight	Ethics oversight was provided by CIMMYT as per the principles described in the organization's 'Ethics in Research' policy (DDG-POL-04-2019)

Note that full information on the approval of the study protocol must also be provided in the manuscript.